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H I OBSERVATIONS OF SA 68-6597: THE FAINTEST BLUE COMPACT DWARF GALAXY.

D.J. Pisano[1,2,3], David C. Koo[1,4,5], Christopher N.A. Willmer[1,4], Kai Gerhard Noeske[1,4], and A.C. Phillips[1,4]

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ABSTRACT

Blue compact dwarf galaxies (BCDs) are faint ($M_B \leq$-17 mag) compact (R<1 kpc), at least qualitatively very blue galaxies due to active star formation, and have low metallicities. Found serendipitously as part of a redshift survey of faint galaxies with the Keck Telescope (DEEP), SA 68-6597 is at a distance of 80 Mpc, and is one of the faintest, -12.4 mag, lowest metallicity, $\sim$0.05 $Z_\odot$, BCDs known. Its Hβ linewidth of σ =27 km s^{-1} and small size, R_{eff} $\sim$190 pc, suggest that it is an extremely low mass galaxy. We have used the Arecibo telescope to measure the H I properties of SA 68-6597 in order to better constrain its total mass and its potential for future star formation. SA 68-6597 has a M_{HI}=(1.4$\pm$0.4)$\times 10^7 M_\odot$ and an H I FWHM linewidth of $33\pm^{60}_{12}$. Combining the H I linewidth with an estimate of the size of the H I disk, we derive a $M_{dyn}\gtrsim 3\times 10^7 M_\odot$. The M_{HI}/L_B=1.0$\pm$0.3$M_\odot/L_\odot$, $M_{dyn}/L_B \geq 2 M_\odot/L_\odot$ and $M_{HI}/M_{dyn} \lesssim 0.47$ values are typical for BCDs. Combining the measured star formation rate of 0.003 $M_\odot$/yr with the H I mass, we derive a gas depletion timescale of 5$\pm$2 Gyr. While SA 68-6597 is a fainter, lower-mass, higher metallicity counterpart to other BCDs like I Zw 18 and SBS 0335-052, its H I properties suggest it will not evolve dramatically in the near future. Given the limits on its gaseous and dynamical masses, SA 68-6597 may be able to evolve into a moderately massive dwarf spheroidal galaxy.

Subject headings: galaxies: dwarf – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: ISM

1. INTRODUCTION

Blue Compact Dwarfs (BCDs) are faint (M_B $\leq$-17 mag, e.g. Kong & Cheng 2002), compact (diameters of the high surface brightness regions of less than 1 kpc, e.g. Thuan & Martin 1981), and blue enough to suggest active star formation (e.g. Gordon & Gottesman 1981; Thuan & Martin 1981). They are typically low metallicity systems (Izotov et al. 1999). Two of the most extreme BCDs, in terms of luminosity, mass, and metallicity, are I Zw 18 and SBS 0335-052. I Zw 18 and SBS 0335-052 have luminosities of -12.8 mag and -14.3 mag, total masses of $10^{8.5-9.5} M_\odot$, HI masses of $10^{7.8-9.3} M_\odot$ (van Zee et al. 1998; Pustilnik et al. 2001), and oxygen abundances of the ionized gas of $12 + log(O/H) = 7.17$ & 7.34 (Izotov et al. 1999)–the lowest known in the universe. Because of these properties, I Zw 18 and SBS 0335-052 are believed to be undergoing early bursts of star formation (Izotov & Thuan 2004; Lipovetsky et al. 1999). While much more luminous, BCD-like, HII galaxies at moderate redshift may evolve into galaxies like NGC 205 (Koo et al. 1994, 1995; Guzmán et al. 1996), these low luminosity, low mass BCDs may be the progenitors of dwarf spheroidal galaxies like Carina.

SA 68-6597 was discovered serendipitously during the first DEEP[6] run using the Keck LRIS instrument(Oke et al. 1995) with a 1200 l/mm grating (Koo et al. 2005, in preparation). This galaxy was selected because of its blue color and visually estimated compact non-stellar appearance and faint apparent magnitude. The LRIS data show that SA 68-6597 has a redshift of z=0.0186 implying that it is intrinsically extremely faint. Assuming a Hubble constant of 70 km s^{-1} Mpc^{-1}, SA 68-6597 is located at a distance of 80 Mpc and has a B magnitude of -12.4 mag as measured by the DEEP.team. Using the combination of the O III[λ5007]/Hβ and the N II[λ6583]/Hα line ratios as measured with HIRES, Koo et al. find that SA 68-6597 has an extremely low excitation temperature, $\sim$14,500 K, and metallicity $12 + log(O/H)$ $\sim$7.4 ($\sim$0.05 $Z_\odot$). This places SA 68-6597 well away from the well-defined locus of H II galaxies (e.g. Lee et al. 2004) and Local Group dwarf irregulars (Mateo 1998) in this parameter space. The most similar galaxy to SA 68-6597 in this space is the BCD SBS 0335-052. Follow-up observations (Koo et al. 2005, in preparation) with Keck HIRES (Vogt et al. 1994) also show that the emission lines have Gaussian velocity dispersions of $\sim$ 27 km/s. HST WFPC2 images reveal a very small galaxy, R_{25} of $1.0\pm^{0.1}_{0.05}{}''= 400\pm^{40}_{20}$ pc. Combined with the small optical linewidth, this implies that SA 68-6597 is a very low mass galaxy, $\sim 10^7 M_\odot$. Based on the flux of the Hα line in the LRIS spectra, the star formation rate of this galaxy, 0.003 $M_\odot$ yr^{-1}, is similar to what is expected for a BCD given its inferred low total mass (Hopkins et al. 2002). These properties from Koo et al. (2005, in preparation) and summarized in Table 1, strongly suggest that SA 68-6597 is a blue compact dwarf that is fainter and smaller than other BCDs (e.g. Thuan & Martin 1981; Salzer et al. 2002). It is a fainter, lower-mass, but slightly higher metallicity counterpart to the more famous BCDs I Zw 18 and SBS

[1] Email: pisano@nrl.navy.mil, koo@ucolick.org, cnaw@ucolick.org, kai@ucolick.org, phillips@ucolick.org
[2] Naval Research Laboratory, Remote Sensing Division, Code 7213, 4555 Overlook Ave. SW, Washington, DC 20375
[3] National Research Council Postdoctoral Fellow
[4] UCO/Lick Observatory, University of California, Santa Cruz, CA 95064
[5] Dept. of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064
[6] Deep Extragalactic Evolutionary Probe: see URL http://deep.ucolick.org

0335-052. It is the faintest known BCD (Koo et al. 2005, in preparation). Its extreme nature makes this galaxy a particularly interesting probe of low mass galaxy formation (see Pustilnik et al. 2001, and references therein for a discussion).

Observations of the 21-cm line of neutral hydrogen (H I) can help us better understand the nature of SA 68-6597. The H I content of SA 68-6597 is an important measure of its potential for future star formation. The current burst of star formation is small in an absolute sense, 0.003 $M_{\odot}$ yr^{-1}, but if the H I mass is also low then it can still rapidly consume its H I and subsequently passively evolve, fade and possibly become a galaxy like the Carina dwarf spheroidal in the Local Group. If the H I mass is much higher, then it is more likely to continue forming stars for a long time and will retain its current appearance. Furthermore, while the optical emission lines have a width of 27 km s^{-1}, this linewidth may not trace the entire gravitational potential of the galaxy. The H I gas tends to trace the gravitational potential to larger radii than the stars or ionized gas. In addition, ionized gas may be tracing galactic outflows; this is less likely for the neutral gas. For all of these reasons, H I provides the best measure of the total, dynamical mass of a galaxy. The dynamical mass is an important constraint on the evolution of a galaxy. If SA 68-6597 has a low total mass, then it may eject its neutral gas before it can consume it in star formation (e.g. Mac Low & Ferrara 1999). If it is higher, then it may be too massive to evolve into a dwarf spheroidal galaxy. In this paper, we report on our Arecibo observations of H I in SA 68-6597. These observations help constrain the potential for future star formation in the galaxy and provide a more robust measure of the total mass of the galaxy constraining the current nature and future evolution of SA 68-6597, and its relation to other BCDs like I Zw 18.

2. ARECIBO H I OBSERVATIONS & REDUCTIONS

We observed SA 68-6597 with the Arecibo[7] 305 m telescope on 2004 August 1–4 and October 3–4. We observed only at night to minimize solar interference. We used the L-wide receiver for all our observations. This receiver has a system temperature of $\sim$27 K, and a gain of $\sim$10 K Jy^{-1} as measured by the Arecibo staff. Both values are weakly dependent on the zenith angle of the observation. Data were processed through the interim correlator in both linear polarizations over total bandwidths of 25 MHz and 12.5 MHz, corresponding to a velocity range of $\sim$5000 km s^{-1} and $\sim$2500 km s^{-1}. Each bandwidth and polarization had 9-level sampling and 2048 channels, resulting in a velocity resolution per channel of 5.2 km s^{-1} and 2.6 km s^{-1}. Our observations utilized a high pass filter to block interference below 1370 MHz contaminating our band. The beam size of the L-wide receiver according to the Arecibo documentation is $3.1' \times 3.5'$. At the distance of SA 68-6597, 80 Mpc, this corresponds to a linear size of 72 kpc$\times$ 81 kpc. As the effective radius of the stellar emission is only 190 pc, this should be more than sufficient to encompass all of the H I associated with this galaxy. Yet this beam size is small enough that there are no known galaxies at a similar redshift that can contaminate our H I measurements; the closest galaxy is $\gtrsim$400 kpc away and there are no known groups within 3 Mpc based on a NED[8] search. It is further unlikely that there are any H I-rich, optically invisible galaxies exist that could contaminate our measurements (Doyle et al. 2005).

We used the standard position switching algorithm for our observations spending 5 minutes on SA 68-6597 followed by 5 minutes offset to blank sky by 5 minutes in right ascension such that we tracked the same azimuth and zenith angle as the on-source scan. This was repeated for all six nights for an on-source integration time of 240 minutes. Our data were reduced using standard Arecibo IDL routines written by Phil Perrilat. Each bandwidth of each scan was calibrated separately and the polarizations were averaged together before a first or second order baseline was fit across the portion of the spectrum clean of any interference. All scans were then averaged together to produce the final spectrum. While some scans showed signatures of interference around 1400 MHz, since SA 68-6597 is at a frequency of 1394 MHz this should not affect our ability to detect the galaxy. The bandpass, however, was significantly better for the 12.5 MHz band as a result of the RFI at 1400 MHz, and so we proceeded only with this band. Because the two bands are split after the first amplification, their noise is not independent and, therefore, it would not have helped to combine these bands. The resulting noise was 0.22 mJy per 2.6 km s^{-1} channel. For analysis, we binned this spectrum by 4 channels to a resolution of 10.8 km s^{-1}, improving the noise to 0.10 mJy per channel. The observational details are listed in Table 1. Our flux measurements of a bright galaxy, UGC 199, are within 17% of previously published values (Schneider et al. 1990). This is a much smaller source of error than that of random noise and can be disregarded for this work.

3. RESULTS

Figure 1 shows the binned H I spectrum of SA 68-6597 near the known optical velocity of the galaxy. The small inset in the lower left corner shows the entire spectrum (excluding the edges of the bandpass). The H I emission is very weak, but clearly detected. The line has a peak flux of 0.31 mJy located at a velocity of 5552 km s^{-1}. This is only a 3σ detection, but it is the brightest feature in the spectrum and is located within $\sim$40 km s^{-1} of the optical velocity of SA 68-6597; which is within the 1σ uncertainties of the optical redshift. To check its reality, we split the raw data into various subsets (e.g. by sets of days, polarization, etc.) and searched for the line in these data. The line was either visible in the subsets or its absence was consistent with the noise levels; thus we believe that it is a real emission line from SA 68-6597.

The vertical dotted lines in Figure 1 indicate the region over which we measured the H I properties of SA 68-6597. The integrated flux is 0.0095$\pm$0.0025 Jy km s^{-1}, which translates to a M_{HI} of $(1.4\pm0.4)\times10^{7} M_{\odot}$–a 3.8σ detection over five channels. We know of no galaxies within the $3.5'$ beam of Arecibo that may be contaminating this

[7] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center which is operated by Cornell University under a Cooperative Agreement with the National Science Foundation.

[8] The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

TABLE 1
Properties of SA 68-6597

Parameter	Value	Units
Optical Properties[a]:		
Right Ascension (J2000)	00:17:15.41	h:m:s
Declination (J2000)	15:48:38.36	$^\circ:':''$
Optical Heliocentric Velocity	5595±40	km s^{-1}
Distance	80	Mpc
Optical Velocity Dispersion	$27\pm^{1}_{2}$	km s^{-1}
Absolute B Magnitude	-12.4	mag
Luminosity	1.4	$10^7 L_\odot$
R_{25}	$400\pm^{40}_{20}$	pc
Star Formation Rate	0.003	$M_\odot$/yr
Observational Properties[b]:		
Time on Source	240	min.
Channel Width (binned)	10.8	km s^{-1}
RMS noise per channel	0.10	mJy
H I Properties[b]:		
Peak Flux	0.31	mJy
Heliocentric Recession Velocity	5557±5	km s^{-1}
Velocity Width (20%)	$51\pm^{93}_{19}$	km s^{-1}
Integrated Flux	9.5±2.5	mJy km s^{-1}
H I Mass	1.4±0.4	10^7M$_\odot$
M_{HI}/L_B	1.0±0.3	$M_\odot/L_\odot$
Gas Depletion Time	5±2	Gyr
M_{dyn}	≥3.0	$10^7 M_\odot$
M_{dyn}/L_B	≥2	$M_\odot/L_\odot$
M_{HI}/M_{dyn}	$\lesssim$0.47	

[a]From Koo et al. (2005), in preparation
[b]this paper

measurement, so we believe that this H I is truly associated with SA 68-6597. Combining these H I data with the optical properties, we find a M_{HI}-to-L_B ratio of 1.0±0.3$M_\odot/L_\odot$. The gas depletion timescale, τ=M_{HI}/SFR, is 5±2 Gyr without accounting for helium, molecular gas, or recycling.

The H I linewidth at 50% of the peak flux, W_{50} (FWHM), is measured to be 32±10 km s^{-1}, centered at 5557±5 km s^{-1}. Again, this is within the uncertainties of the optical recession velocity. Because of the low signal-to-noise ratio of the detection, this value is highly imprecise and potentially inaccurate. To address this issue, we have used a Monte Carlo simulation of a Gaussian line with a peak signal-to-noise ratio of 3σ to relate the measured FWHM to the true FWHM. We find that the the true H I FWHM = $33\pm^{60}_{12}$ km s^{-1}. Converting this to a W_{20} yields $51\pm^{93}_{19}$ km s^{-1}, assuming a Gaussian lineshape.

One of the main goals of our project is to determine the dynamical mass, M_{dyn}, of SA 68-6597 using the H I line. As discussed in Section 1, the H I line is generally believed to be a more reliable tracer of the gravitational potential than the Hβ line. Because of the large uncertainties associated with our H I measurement, and the additional uncertainties from the unknown inclination of SA 68-6597, we are practically restricted to calculating a lower limit to M_{dyn}. We follow the same procedure to derive the dynamical mass as in Pisano et al. (2001) using the following standard formula assuming the H I is in circular rotation: $M_{dyn}(<R) \geq V_{rot}^2 \times R/G$.

In this case we take V_{rot} to be half of the lower limit on W_{20} uncorrected for inclination, for the radius we scale R_{25} using a canonical scaling factor from Broeils & Rhee (1997) to get R_{HI}=680$\pm^{210}_{200}$ pc. If we use these values to calculate a lower limit to M_{dyn}, we find it is greater than 3.0×10$^7 M_\odot$. This yields M_{HI}/ M_{dyn} ≤ 0.47, and M_{dyn}/L_B≥2. See Pisano et al. (2001) for a discussion of the uncertainties involved in this calculation. All of these measured and derived properties of SA 68-6597 are summarized in Table 1.

4. DISCUSSION

Our H I observations have revealed that SA 68-6597 is not only a low luminosity galaxy, but also has a low M_{HI}, and probably a low M_{dyn} as well. By all three measures, SA 68-6597 reveals itself to be an extreme cousin of other BCDs. BCDs typically have M_{HI}∼10$^{8-9}M_\odot$, with only a few as low as 10$^7M_\odot$ or as high as 10$^{10}M_\odot$. They have M_{dyn}∼10$^{8-10}M_\odot$, and L_B∼10$^{8-10}L_\odot$ (Chamaraux 1977; Thuan & Martin 1981; Hoffman et al. 1989; Staveley-Smith et al. 1992; Thuan et al. 1999; Salzer et al. 2002). SA 68-6597 represents the extreme low mass, low luminosity end of BCDs and is not a distinctly different class of galaxy as generally evidenced by its scale-free properties, such as the H I-mass-to-light ratio, M_{HI}/L_B, and the gas-mass fraction, M_{HI}/M_{dyn}.

SA 68-6597 has an M_{HI}/L_B ratio that is consistent with that of the large samples of BCDs studied by Staveley-Smith et al. (1992); van Zee et al. (1998, 2001); Salzer et al. (2002); Hoffman et al. (2003); Thuan et al. (2004) who found ratios ranging from ∼0.33-1.46 $M_\odot/L_\odot$. SA 68-6597's H I mass-to-light ratio is even within the range for luminous compact blue galaxies studied by Garland et al. (2004), but is about twice the median value. Only the study of Hoffman et al. (1989) found a significantly lower M_{HI}/L_B value for 11 Virgo cluster BCDs of 0.04 $M_\odot/L_\odot$. The M_{HI}/M_{dyn} values for BCDs are also generally consistent with SA 68-6597's upper limit of 0.47. A variety of studies of BCDS find M_{HI}/M_{dyn} ratios ranging from 0.01-0.78 (Hoffman et al. 1989; van Zee et al. 1998; Hoffman et al. 2003; Thuan et al. 2004). The ratio of dynamical mass-to-light, M_{dyn}/L_B, for other BCDs ranges from 0.18-2.62 $M_\odot/L_\odot$ (Hoffman et al. 1989; Staveley-Smith et al. 1992; Thuan et al. 2004), which is also consistent with the lower limit of 2 $M_\odot/L_\odot$ for SA 68-6597. It's SFR and M_{HI} are consistent with expectations for BCDs based on SA 68-6597's H I linewidth (Hopkins et al. 2002). Even luminous compact blue galaxies have a median M_{dyn}/L_B only slightly higher (5 $M_\odot/L_\odot$) than that of SA 68-6597(Garland et al. 2004). All of these ratios suggest that SA 68-6597 is an extremely faint, extremely low-mass version of a typical blue compact dwarf.

In terms of individual BCDs, SA 68-6597 is quite similar in its gaseous properties to I Zw 18 and Haro 4. I Zw 18 is still slightly more massive and more luminous with a M_{HI} = 2.6×10$^7M_\odot$, M_{dyn}=2.6×10$^8M_\odot$, and L_B = 3.5×10$^7L_\odot$ (van Zee et al. 1998). Nevertheless, with M_{HI}/L_B = 0.7 and M_{dyn}/L_B = 5 I Zw 18 has mass-to-light ratios nearly identical to SA 68-6597. Its gas-mass fraction of 0.1 is also similar to SA 68-6597. Haro 4 is slightly less similar with M_{HI} = 2×10$^7M_\odot$, M_{HI}/L_B = 0.17$M_\odot/L_\odot$, M_{dyn}=5×10$^8M_\odot$, M_{dyn}/L_B = 4.8$M_\odot/L_\odot$, and M_{HI}/M_{dyn}=0.03 (Bravo-Alfaro et al. 2004). While M_{HI}, M_{dyn}, and M_{dyn}/L_B of Haro 4 are close to those of SA 68-6597, the M_{HI}/L_B is lower, and the gas-mass

fraction is lower than SA 68-6597, but still consistent with it.

The question is then raised: "what do these properties say about the evolutionary path of SA 68-6597?" Our derived gas depletion timescale, τ, for SA 68-6597 is 5±2 Gyr. This value provides a rough measure of the time it will take for SA 68-6597 to consume all of its gas at its current rate of star formation (Kennicutt 1983). This is similar to many of the measured values for a sample of 21 BCDs from Hopkins et al. (2002), but is much greater than a sample of 15 BCDs studied by Sage et al. (1992). It has a gas depletion timescale equal to the median value for the sample of field and cluster galaxies studied by Kennicutt (1983). SA 68-6597 has a larger τ than either I Zw 18 or SBS 0355-052 (Hopkins et al. 2002). It has a shorter τ than all Local Group dwarf irregular galaxies except IC 10 and NGC 6822 (Mateo 1998). Our estimate does not account for the contribution of helium, recycling of gas, molecular gas, a decreasing SFR or less than 100% star formation efficiency–all of which would increase τ– or the possible effects of outflow–which would decrease τ. Mac Low & Ferrara (1999) suggest that galaxies with gas masses below $10^6 M_\odot$ can suffer complete blowout of their gas, while galaxies between 10^6 and $10^7 M_\odot$ may suffer partial blowout. Because the derived gas mass of SA 68-6597 is $\sim 10^7 M_\odot$, we expect that it could only have a partial outflow (Mac Low & Ferrara 1999). The results of Mac Low & Ferrara (1999) are based on a dark matter halo approximately 10-100× larger than the gas mass. Overall, this means that, SA 68-6597 should evolve in a similar fashion to many less extreme BCDs and normal spiral and irregular galaxies; it will not rapidly consume its gas and passively evolve in the near future. The large M_{dyn} of SA 68-6597 implies that if and when it consumes all its gas, it may be able to evolve into a moderate mass analog of the Local Group dwarf spheroidals (Mateo 1998).

While the low signal-to-noise ratio of our observations make our velocity widths very uncertain, it is worth noting a potentially interesting property of SA 68-6597. The Hβ velocity dispersion of SA 68-6597 is $27\pm^{1}_{2}$ km s^{-1}, while the H I dispersion is $14\pm^{25}_{5}$ km s^{-1}. If the H I linewidth is actually smaller than that of the ionized gas, then we may be seeing evidence of a galactic outflow in SA 68-6597. Such outflows could result in partial blowout of the ISM in the galaxy of anywhere between $\lesssim$1% to 100% (Mac Low & Ferrara 1999) potentially reducing the gas depletion time. Outflows can also be particularly efficient at ejecting metals into the intergalactic medium (Mac Low & Ferrara 1999; Ferrara & Tolstoy 2000) permitting a galaxy like SA 68-6597 to form many generations of stars while maintaining its very low metallicity. Clearly more sensitive and detailed H I observations are needed to address this issue.

5. CONCLUSIONS

We have observed the recently discovered blue compact dwarf galaxy, SA 68-6597, with the Arecibo telescope to determine its gas content and better constrain its total mass using the H I line. SA 68-6597 is one of the faintest, lowest metallicity BCDs known.

SA 68-6597 has properties which indicate it is a typical blue compact dwarf galaxy in all ways, except for its extremely low luminosity and small H I and dynamical masses. In this way it represents the faint, low mass tail of the distribution of BCD properties. It is slightly fainter and less massive than the famous BCD I Zw 18 and only slightly more metal rich. SA 68-6597's gas depletion timescale is similar to the value for other BCDs and normal field galaxies, yet is shorter than most dwarf irregulars in the Local Group. Nevertheless, SA 68-6597 can continue to form stars at its current, prolific rate for almost 5 Gyr and would, therefore, be unlikely to fade significantly in that time. When it does fade, its relatively large dynamical mass suggests it may be able to evolve into a massive dwarf spheroidal galaxy. Its future evolutionary path remains murky.

Because of the combination of the distance and low H I mass of SA 68-6597, our detection was only at the 3σ level, meaning that the measured linewidth and derived dynamical mass are poorly constrained. Nevertheless, the most probable value of the H I linewidth is less than the measured Hβ linewidth indicating that galactic outflows may be present in SA 68-6597. Because of the potential implications of such a situation on SA 68-6597's evolution, more sensitive, spatially resolved H I observations of SA 68-6597 are essential to unravel its current nature and reveal its evolutionary path.

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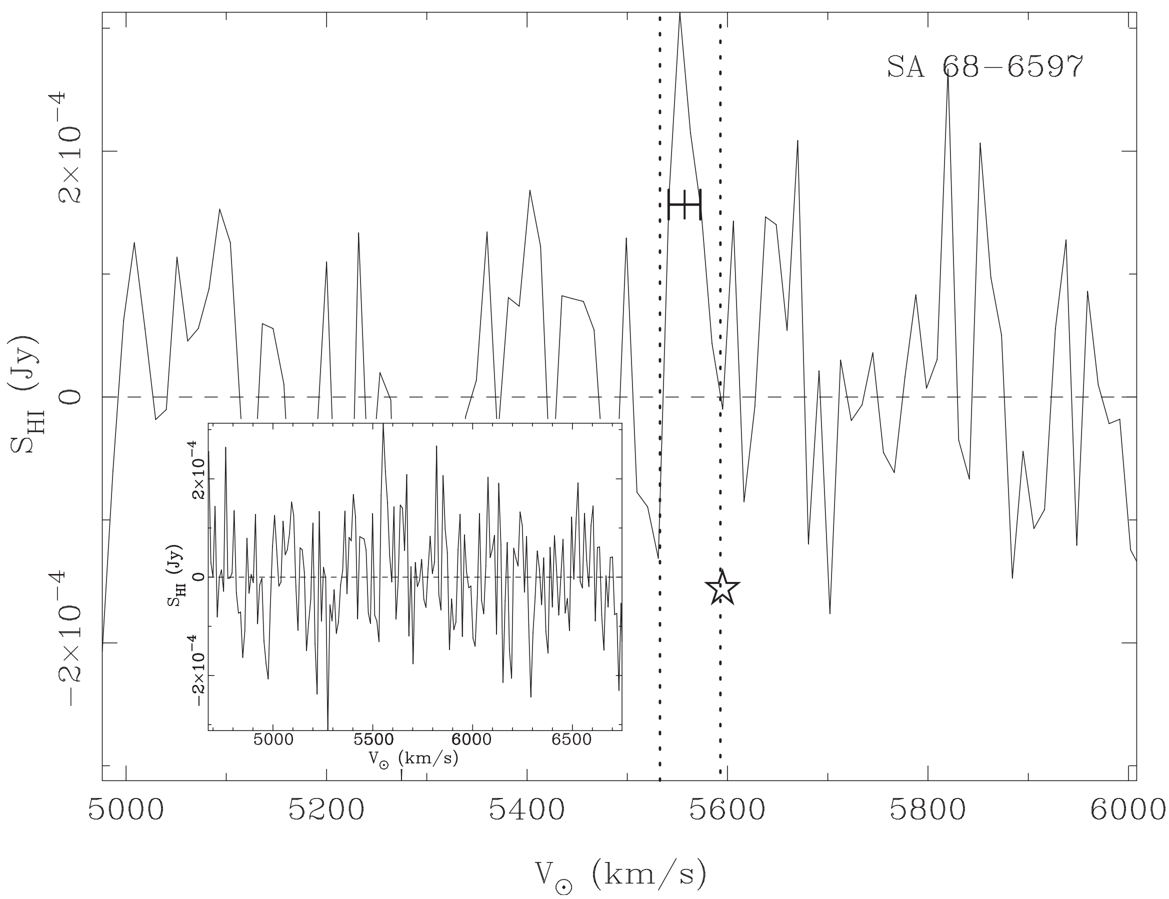

Fig. 1.— A plot of a portion of the Arecibo H I spectrum. The dashed line indicates the origin, while the vertical dotted lines indicate the range over which the line was measured. The vertical tick marks the H I recession velocity of the galaxy, while the star indicates the optical recession velocity. The horizontal solid line indicates the measured H I FWHM. The inset shows the entire Arecibo bandpass (excluding the edges) illustrating that this line is the brightest feature in the spectrum.